LEUTL: A SASE FEL operating down to 130 nm

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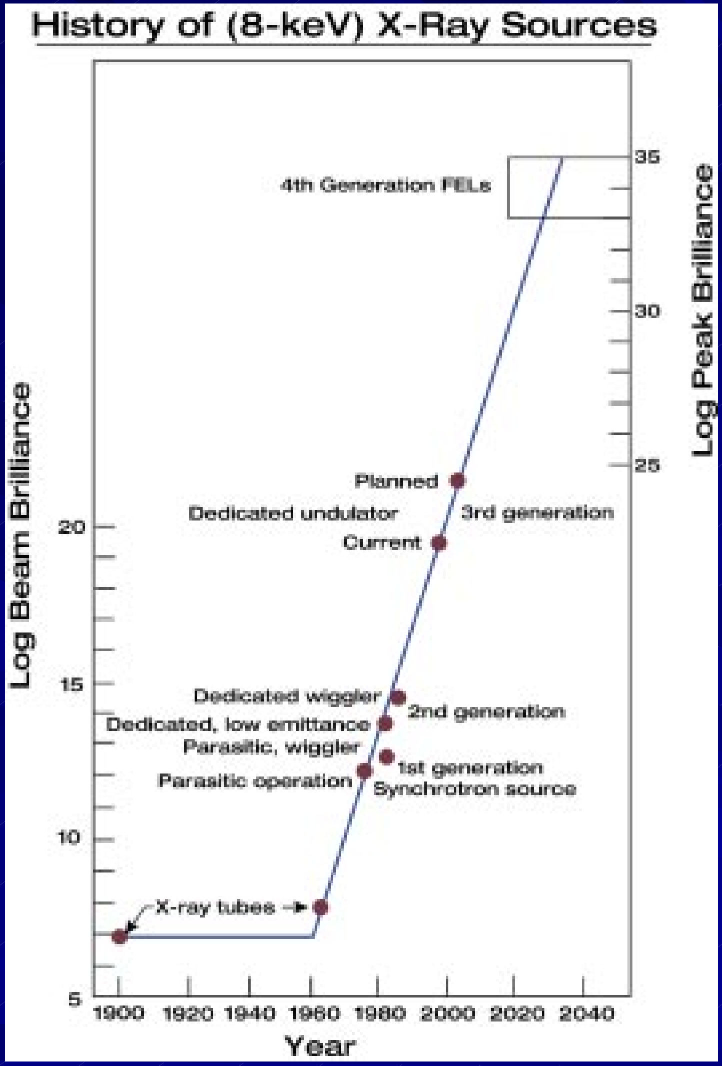
Center for Beam Physics Seminar, LBL 18 Jan 2002



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Recently, there have been a number of experiments that have challenged the single-pass, high-gain FEL theories

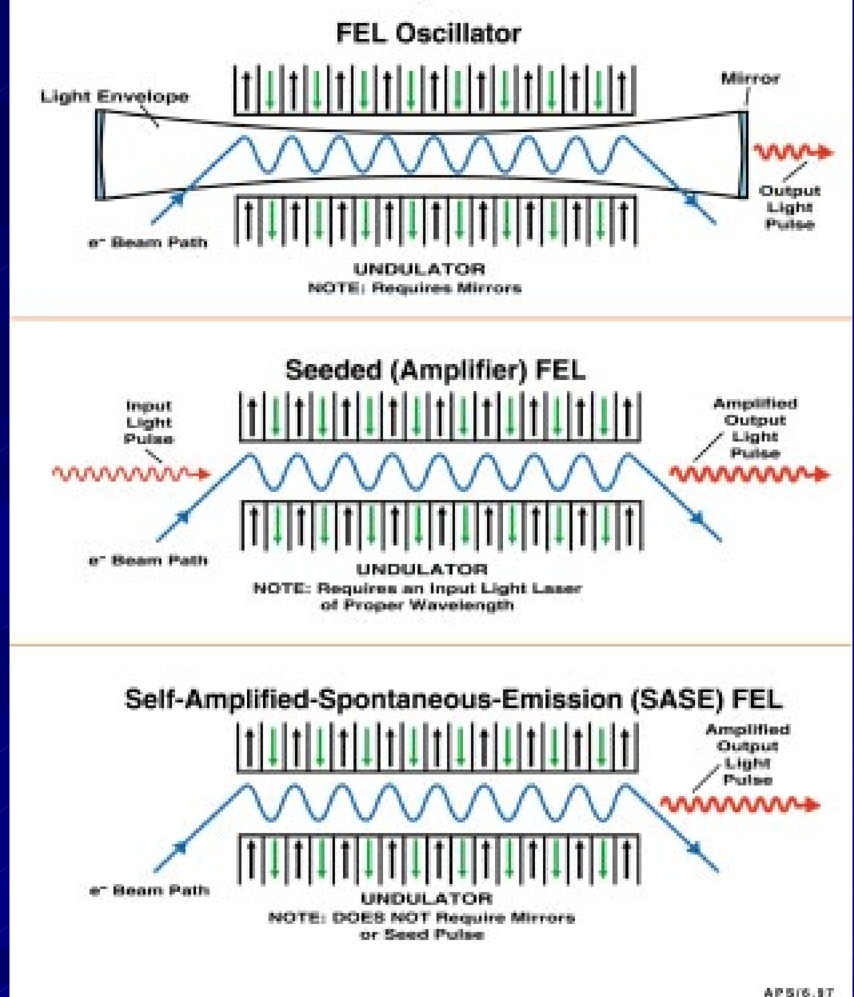
HGHG

- BNL/APS collaboration at BNL Accelerator Test Facility
  Saturation of in a seeded, up-conversion mode at 5.3 _m

SASE

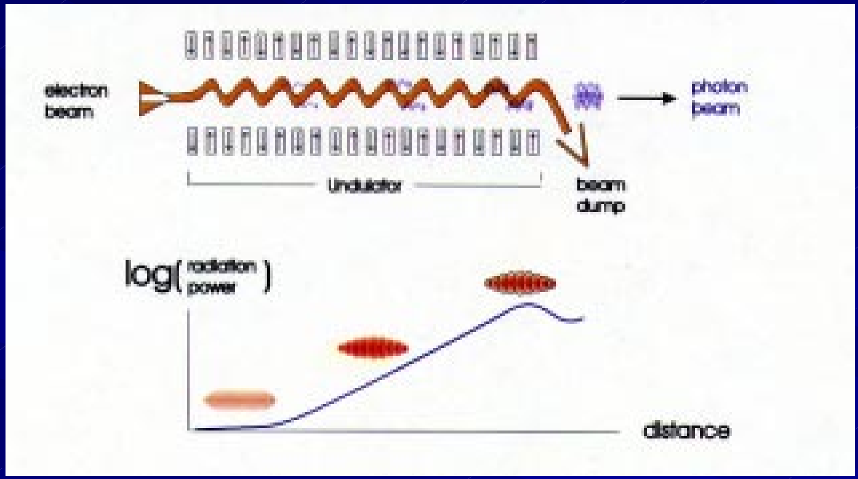
- APS SASE FEL at APS
  Saturation of SASE at 530 and 385 nm and ultra-high gain at 255 and 130 nm
- Tesla Test Facility at DESY (SASE)
  Gain down to 80 nm and saturation at 98 nm
- VISA collaboration at BNL Accelerator Test Facility (SASE)
  Saturation at 800 nm

FEL Systems



FEL Oscillator
Light Envelope
Mirror
Output Light Pulse
e⁻ Beam Path
UNDULATOR
NOTE: Requires Mirrors
Seeded (Amplifier) FEL
Input Light Pulse
Amplified Output Light Pulse
e⁻ Beam Path
UNDULATOR
NOTE: Requires an Input Light Laser of Proper Wavelength
Self-Amplified-Spontaneous-Emission (SASE) FEL
Amplified Output Light Pulse
e⁻ Beam Path
UNDULATOR
NOTE: DOES NOT Require Mirrors or Seed Pulse
APS/6.97

Self-Amplified Spontaneous Emission

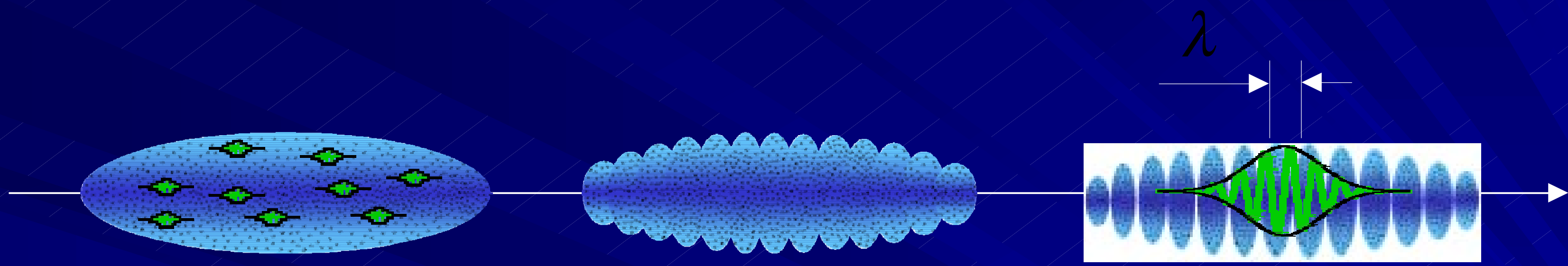


Electrons are bunched under the influence of the light that they radiate.
The bunch dimensions are characteristic of the wavelength of the light.
Excerpted from the TESLA Technical Design Report, released March 2001

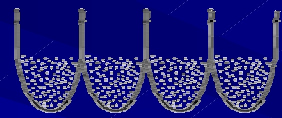
Past Notable SASE Experiments

- MIT ~ 580 µm 1989
  Phys. Fluids B **1** (7) July 1989
- UCLA/LANL ~ 16 µm 1997
  Phys. Rev. Lett. **80** (2) Jan. 1998
- HGHG (ANL/BNL) ~ 5 µm 1999
  Science, **289** Aug. 2000

e-Beam Microbunching



$P \sim N_e$



$P \sim N_e \bullet N_{l_c}$

P - Radiation Power

N_e - Number of particles in the bunch

$E_u + E_R \Rightarrow$ potential wells

N_{l_c} - Number of particles in coherence volume

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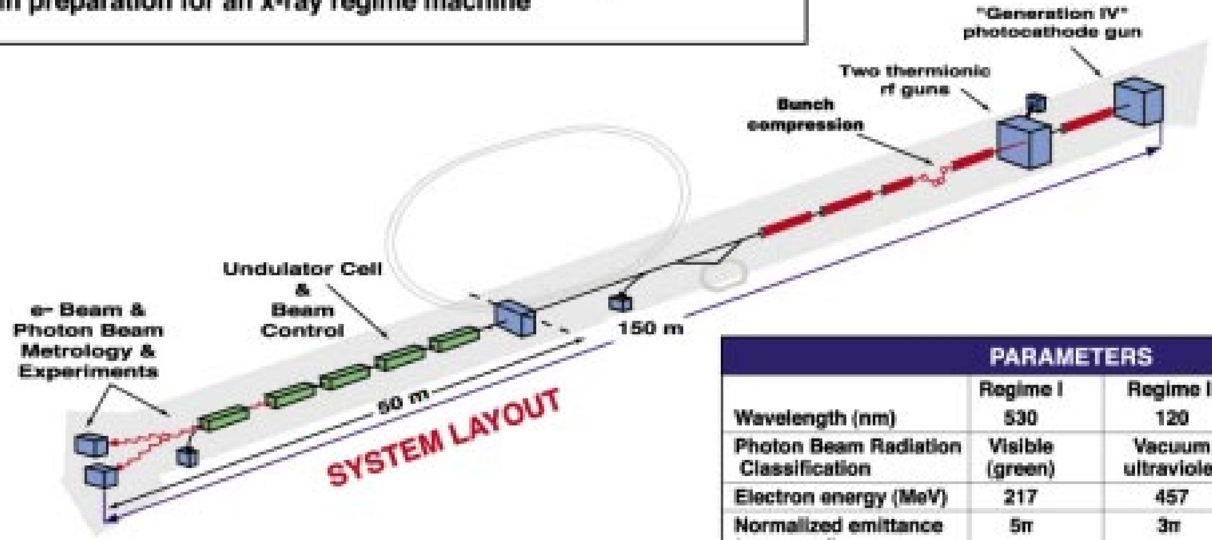
LOW-ENERGY UNDULATOR TEST LINE PARAMETERS

PROJECT GOALS

- Perform experiments with the SASE FEL output
- Assess the challenges associated with producing a SASE FEL in preparation for an x-ray regime machine



PARAMETERS

	Regime I	Regime II	Regime III
Wavelength (nm)	530	120	51
Photon Beam Radiation Classification	Visible (green)	Vacuum ultraviolet	Vacuum ultraviolet
Electron energy (MeV)	217	457	700
Normalized emittance (mm mrad)	5π	3π	3π
Energy spread (%)	0.1	0.1	0.1
Peak current (A)	100	300	500
Undulator period (mm)	33	33	33
Magnetic field (T)	1.0	1.0	1.0
Undulator gap (mm)	9.3	9.3	9.3
Cell length (m)	2.73	2.73	2.73
Gain length (m)	0.81	0.72	1.2
Undulator length (m)	9 x 2.4	9 x 2.4	10 x 2.4

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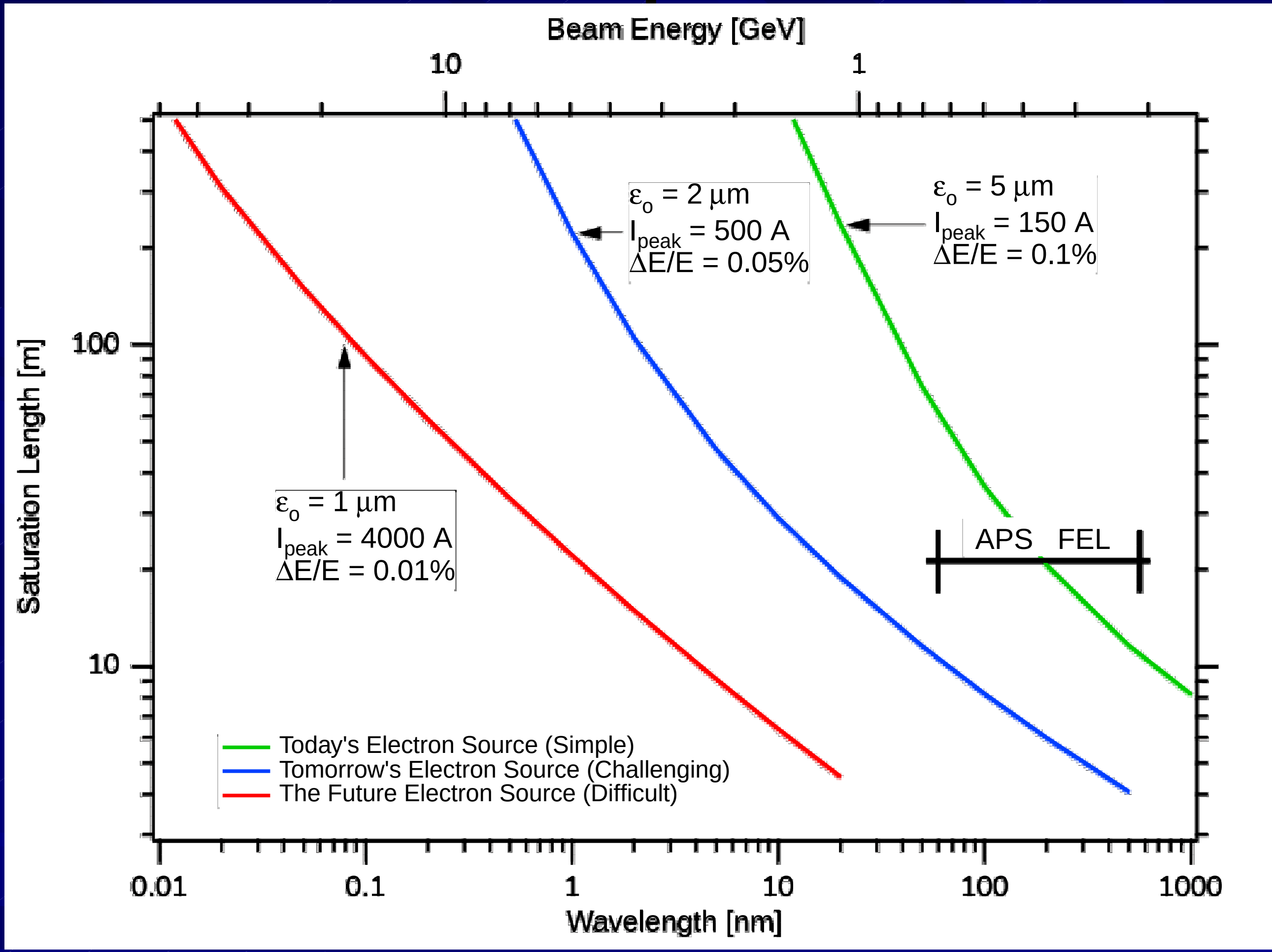
Beam Requirements



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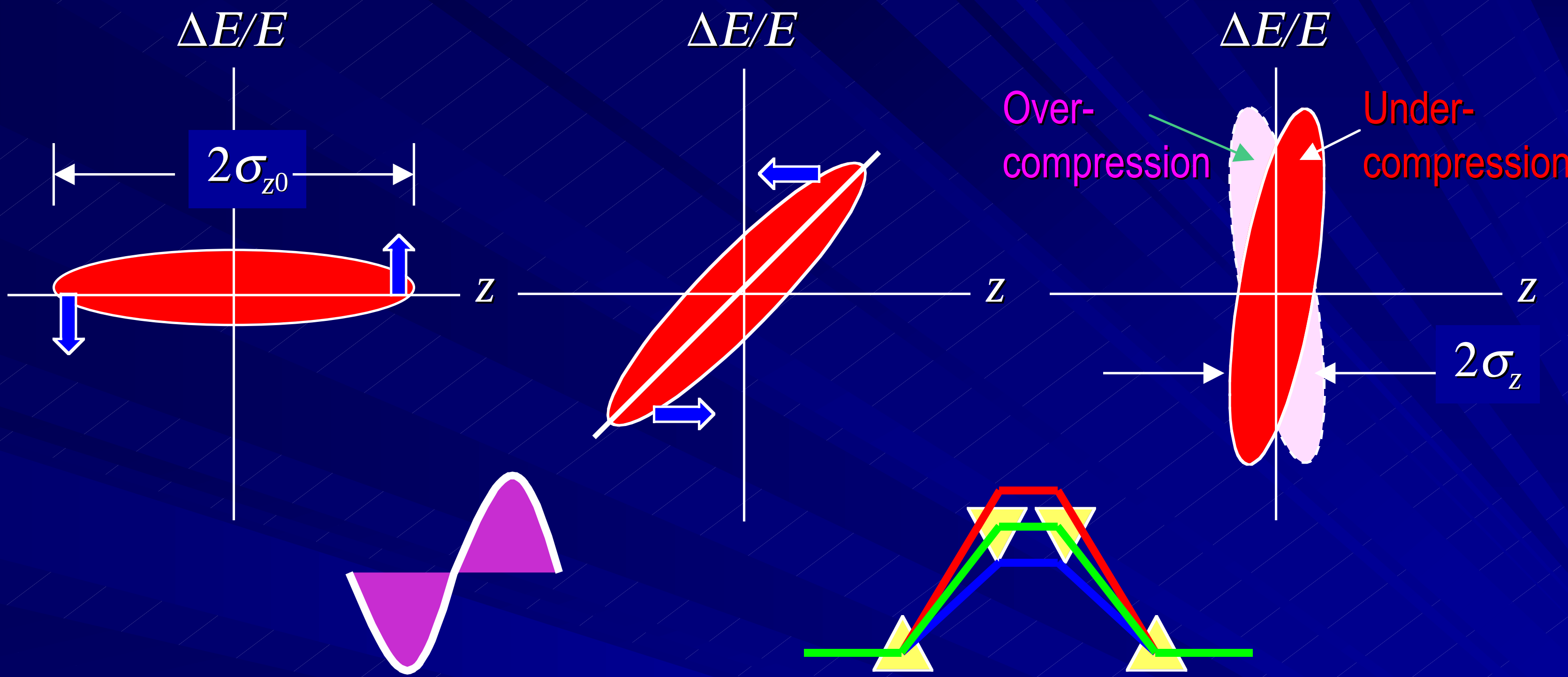


$V = V_0 \sin(\omega\tau)$

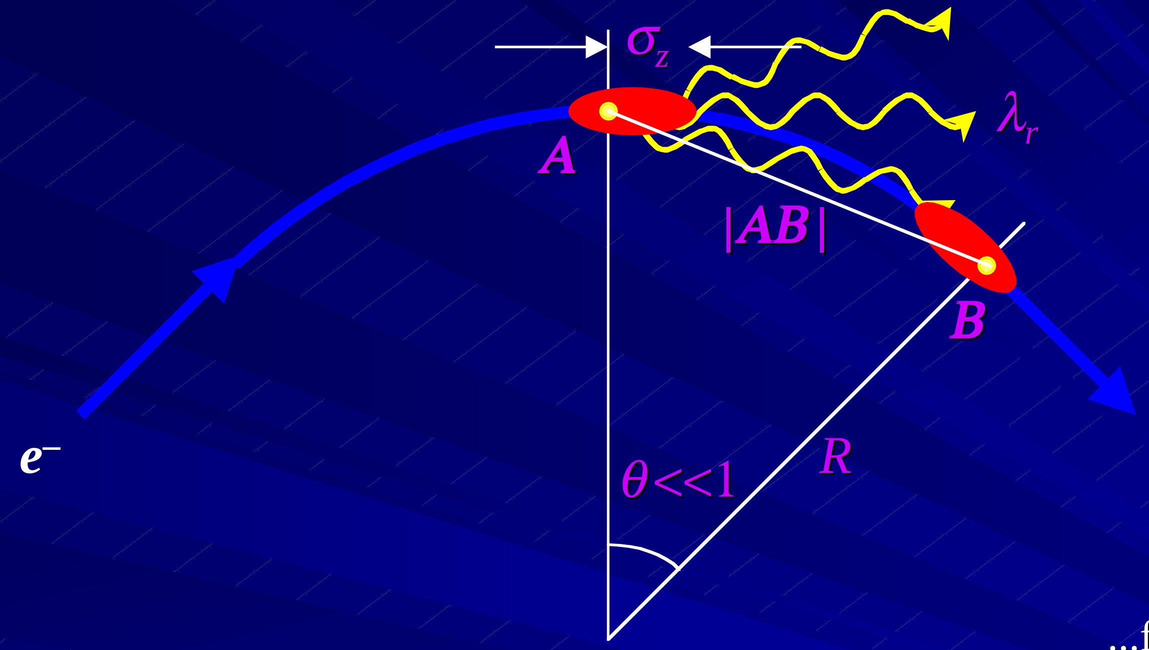
$\Delta z = R_{56}\Delta E/E$

RF Accelerating Voltage

Path Length-Energy Dependent Beamline

Drawings from SLAC/LCLS

Coherent Synchrotron Radiation (CSR)



Coherent radiation for:
$\lambda_r \gg \sigma_z$

...from Derbenev, et. al.

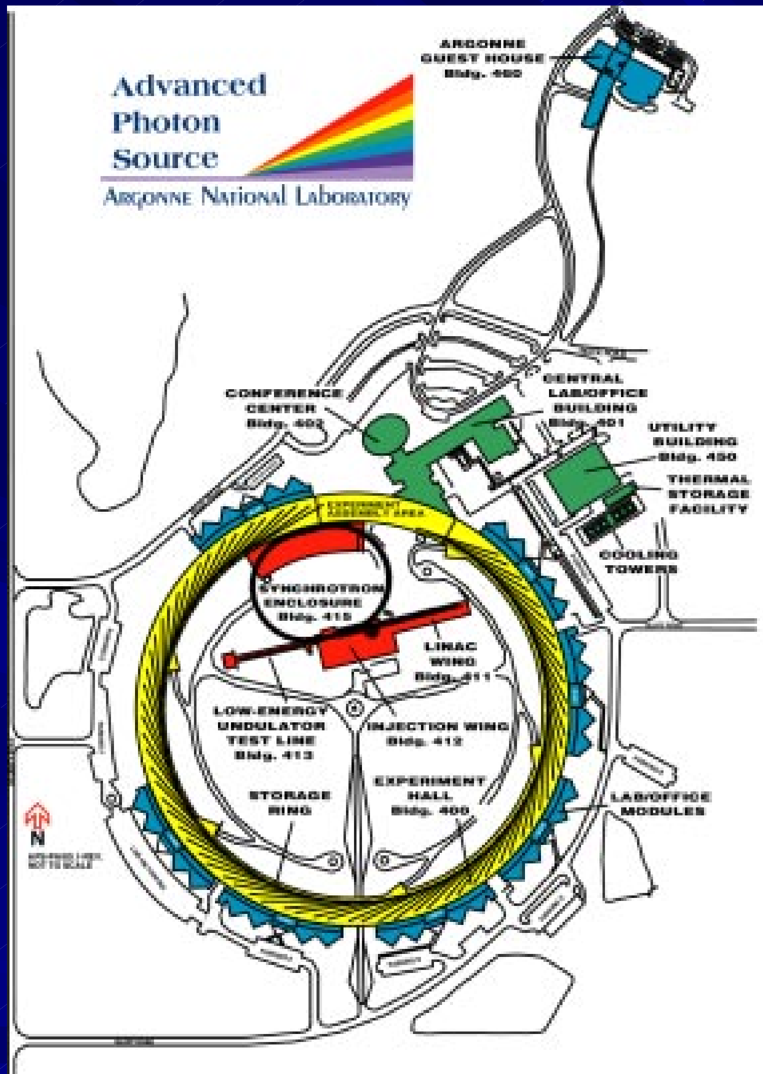
Free space radiation from bunch tail at point ***A*** overtakes bunch head, a distance s ahead of the source, at the point ***B*** which satisfies...

$$s = \mathrm{arc}(AB) - |AB| = R\theta - 2R\sin(\theta/2) \approx R\theta^3/24$$

and for $s = \sigma_z$ (rms bunch length) the overtaking distance is...

$$L_0 \equiv |AB| \approx (24\sigma_z R^2)^{1/3},\ \ (\text{ LCLS}: L_0 \sim 1\ \text{m})$$

Drawings from SLAC/LCLS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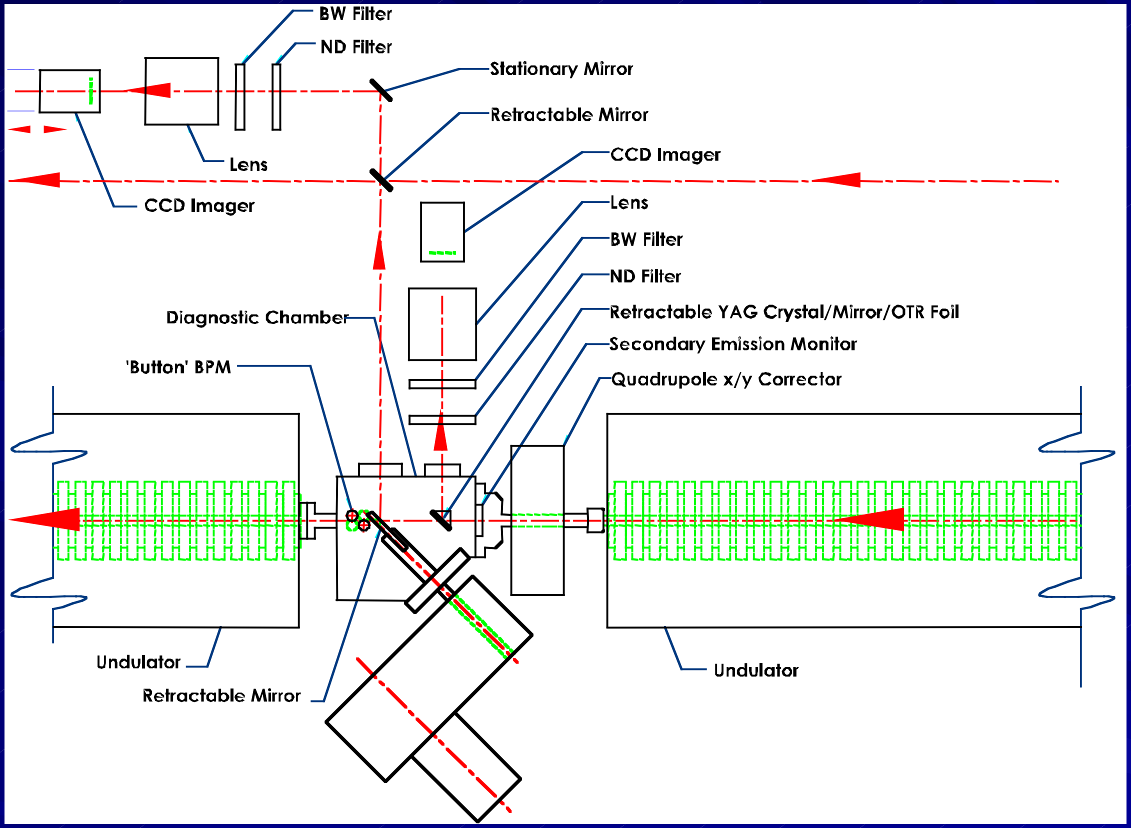
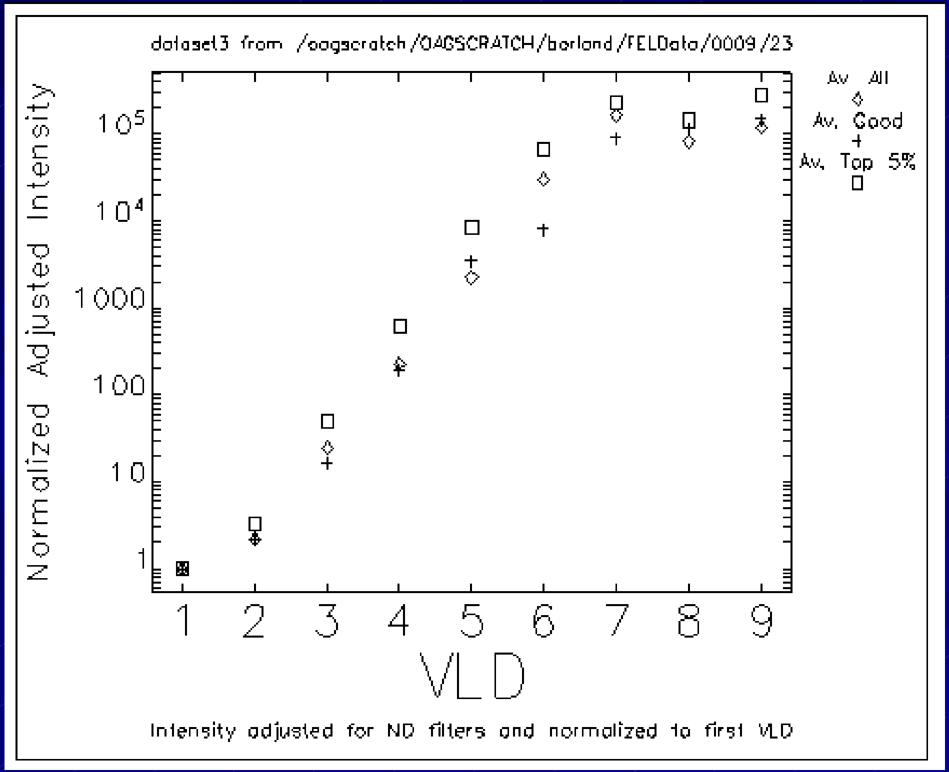
THERMAL STORAGE FACILITY
COOLING TOWERS
SYNCHROTRON ENCLOSURE Bldg. 415
LINAC WING Bldg. 411
LOW-ENERGY UNDULATOR TEST LINE Bldg. 413
INJECTION WING Bldg. 412
STORAGE RING
EXPERIMENT HALL Bldg. 400
LAB/OFFICE MODULES
N



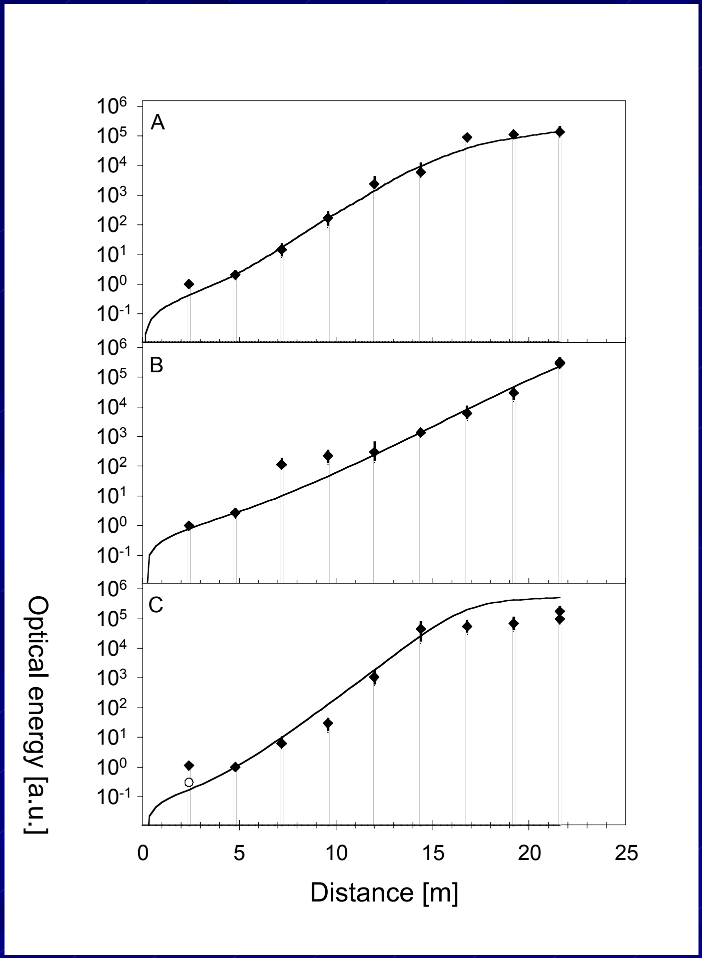
BW Filter
ND Filter
Stationary Mirror
Retractable Mirror
CCD Imager
Lens
CCD Imager
Lens
BW Filter
ND Filter
Diagnostic Chamber
Retractable YAG Crystal/Mirror/OTR Foil
Secondary Emission Monitor
'Button' BPM
Quadrupole x/y Corrector
Undulator
Undulator
Retractable Mirror

530 nm Energy vs. Distance along the Undulator
23 September 2000



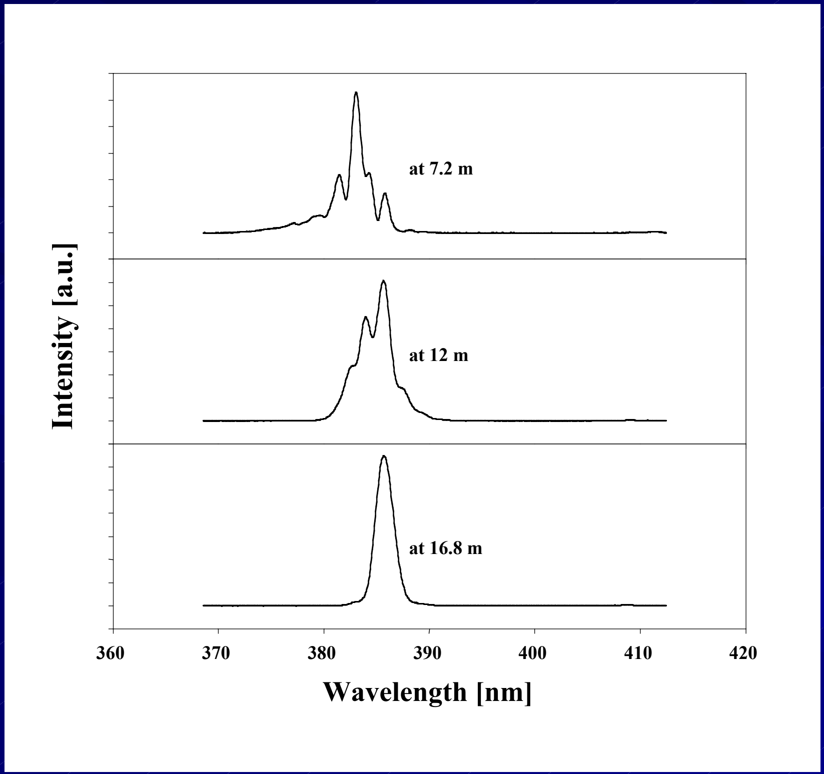
Flash of UV light (385 nm) near saturation. The expected wavelength as a function of angle (radial offset) is clearly seen. The darker “lines” are from shadows of secondary emission monitors in the vacuum chamber.

Optical beam energy (time integrated power) as a function of distance down the undulator, under various electron beam conditions. A) Table 1 Column A 530-nm saturated conditions. B) Table 1 Column B 530-nm unsaturated conditions. C) Table 1 Column C 385_nm saturated conditions. The solid curves are GINGER simulation results.



Measured beam parameters, measured gain length, calculated gain lengths, and radiation mode properties.

	A	B	C
Charge [nC]	0.30 ? 0.02	0.33 ? 0.007	0.30 ? 0.02
RMS bunch length [ps]	0.19 ? 0.02	0.77 ? 0.05	0.65 ? 0.05
Peak Current [A]	630 ? 78	171 ? 12	184 ? 19
Norm. Emittance [? mm-mrad]	8.5 ? 0.9	8.5 ? 1.1	7.1 ? 0.5
RMS energy spread [%]	0.4 ? 0.1	0.2 ? 0.1	0.1 ? 0.1
Nominal radiation wavelength [nm]	530	530	385
Measured gain length [m]	0.97	1.4	0.76
Calculated gain length [m]	1.0	1.3	0.80
Calc. FWHM angular divergence [mrad]	0.58	0.51	0.55
Meas. FWHM angular divergence [mrad]	0.55 -> 1.1	0.76 -> 1.2	0.71 -> 1.2



Measured Optical Spectra as a function of distance along the undulator line at 385 nm. Narrowing of the spectra and a reduction of the number of spikes as the SASE process approaches saturation are clearly observed.

SASE Spectra – 385 nm

Measurement Simulation

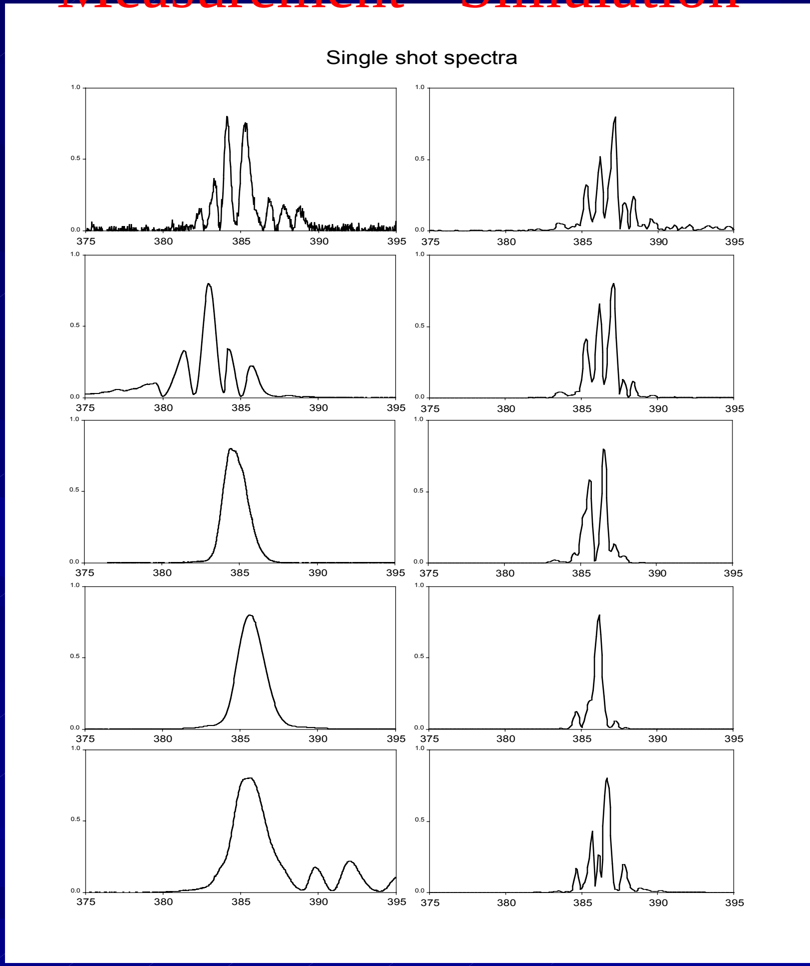
VLD2 (4.8 m)

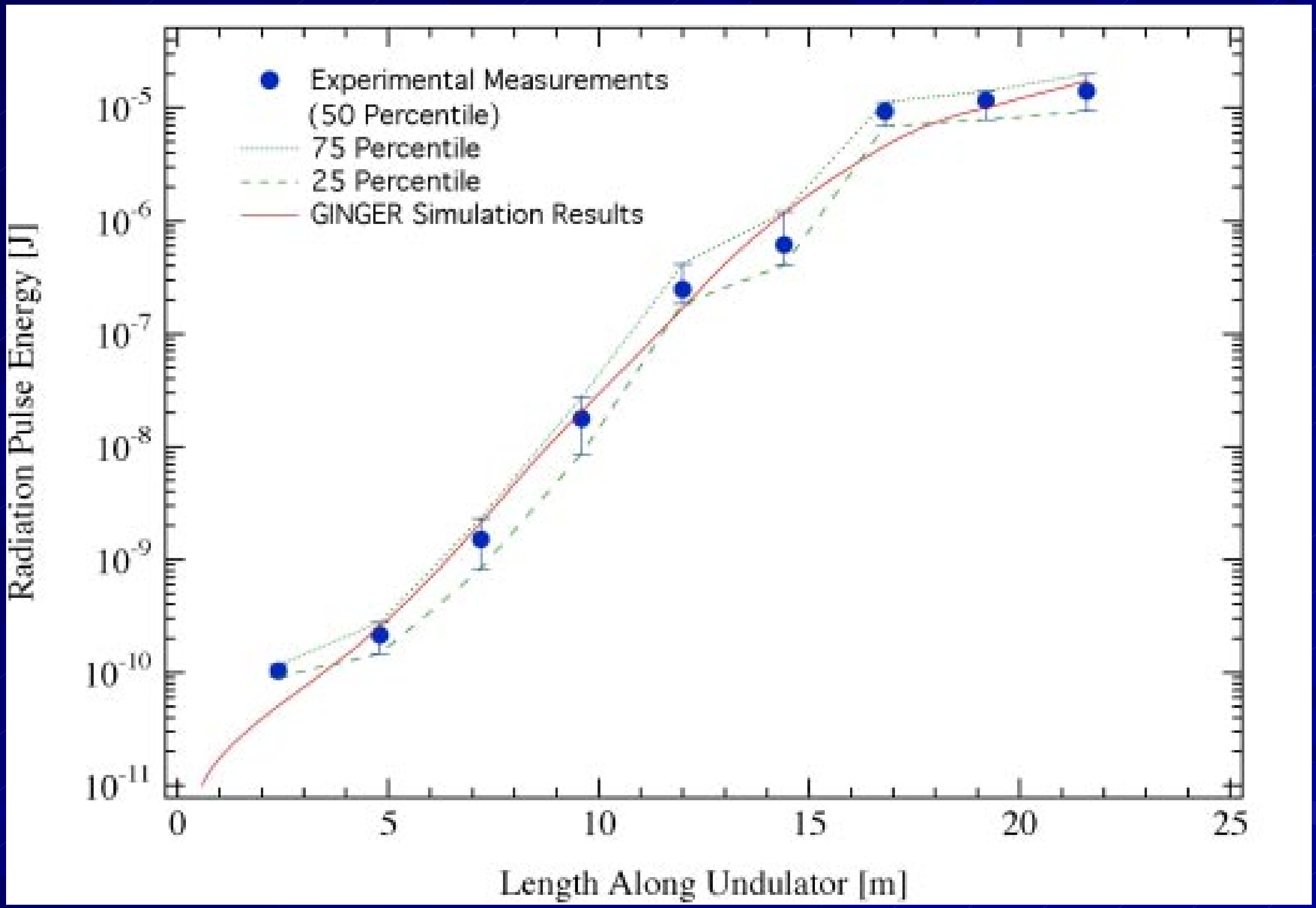
VLD3 (7.2 m)

VLD5 (12 m)

VLD7 (16.8 m)

VLD9 (21.6 m)





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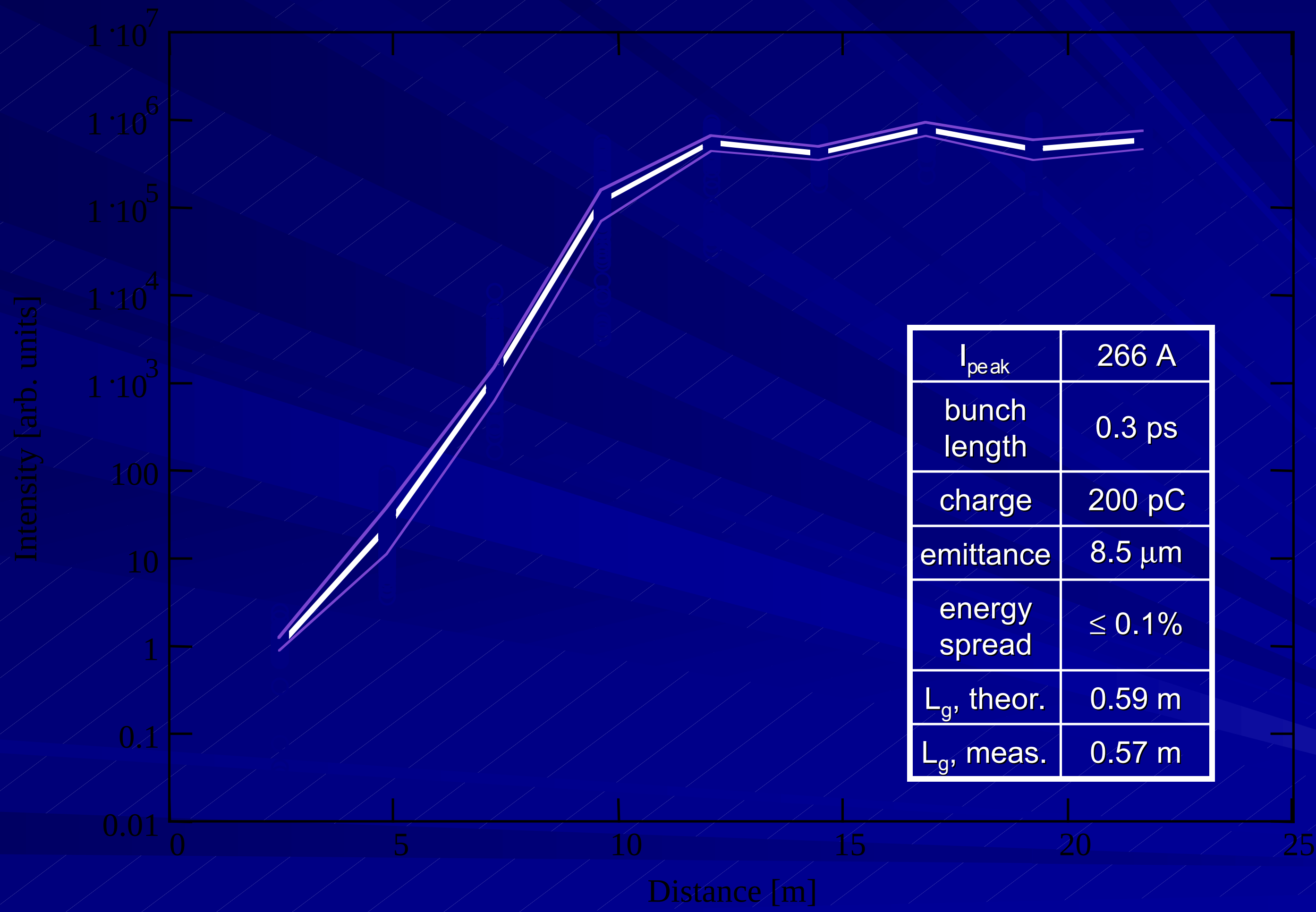
Optical Intensity Gain



I_{peak}	266 A
bunch length	0.3 ps
charge	200 pC
emittance	8.5 µm
energy spread	≤ 0.1%
L_g, theor.	0.59 m
L_g, meas.	0.57 m

530nm
10 March 01
dataset DS1

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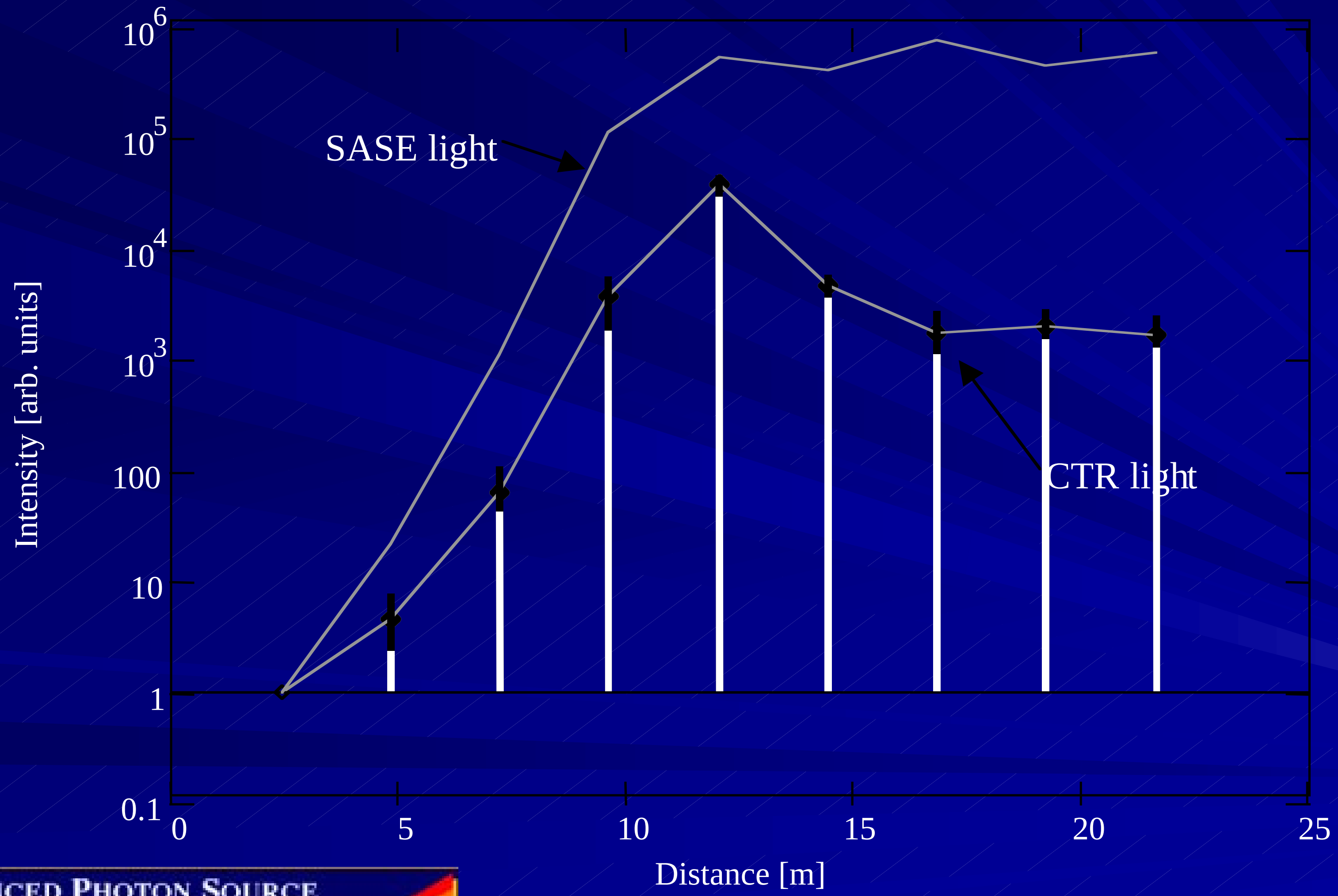
Microbunching Measurement



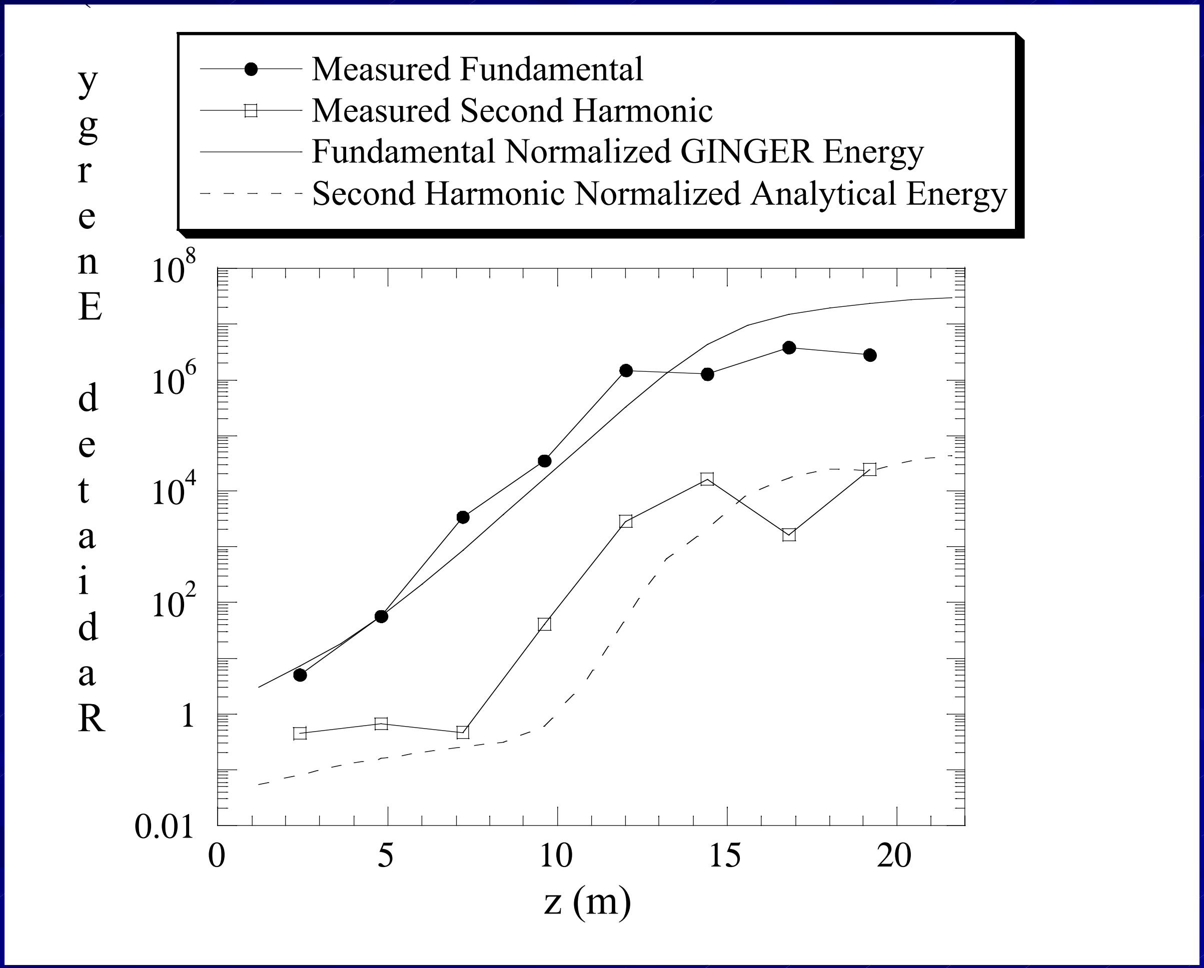
Nonlinear harmonic generation in high-gain free-electron lasers

- Nonlinear harmonic generation in FELs is a promising method to reach shorter wavelengths with more ease than the current designs allow.

- In such a process, coupling between bunching at the fundamental and higher harmonics leads to high gain and nearly simultaneous saturation. *The odd harmonics are favored as they couple more closely to the natural undulative motion of the electron beam through the magnetic device.*

- Nonlinear harmonic radiation can itself be an output source or, alternatively, serve as a seed for further FEL amplification at shorter wavelengths.

Measured fundamental and second harmonic UR energy from 16 August 2001 compared with the simulation and analytic predictions.



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Analytical Energy

- We used GINGER to simulate the expected performance of our system.

- GINGER is able to simulate the short-pulse case regime that we were running in, including start up from noise, but it cannot examine the energies of the nonlinear harmonic emission. Recall that it can examine the fundamental energy and microbunching at the fundamental and nonlinear harmonics.

- We ran and then averaged four GINGER simulations to demonstrate, on average, the predicted SASE emission.

- We then employed an analytical model that allowed us to use the bunching factors for the fundamental and second harmonic and the energy of the fundamental radiation from the GINGER simulations to obtain a theoretical estimate for the second harmonic energy. This model relates the second harmonic energy, E_2, to the fundamental energy E_1, and is given by

$$E_2 \approx E_1 \left(\frac{K}{\gamma_0 k_u \sigma_x} \right)^2 \left(\frac{K_2}{K_1} \right)^2 \left(\frac{b_2}{b_1} \right)^2 .$$

Here, K is the undulator parameter, _ is the relativistic factor of the electron beam, k_u is the wavenumber of the undulator period, $\_{x}$ is the average rms electron beam size in the wiggling plane, and K_1 and K_2 are the effective coupling strength factors due to the fundamental and second harmonic radiation, respectively, and b_1 and b_2 are the microbunching factors of the electron beam at the fundamental and second harmonic wavelengths, respectively. Note the effective coupling strengths and are expressed in terms of Bessel functions and are given by:

$$K_h = K(-1)^{(h-1)/2}\left[J_{(h-1)/2}(h\xi) - J_{(h+1)/2}(h\xi)\right]$$

for h = 1, 3, 5, … and by

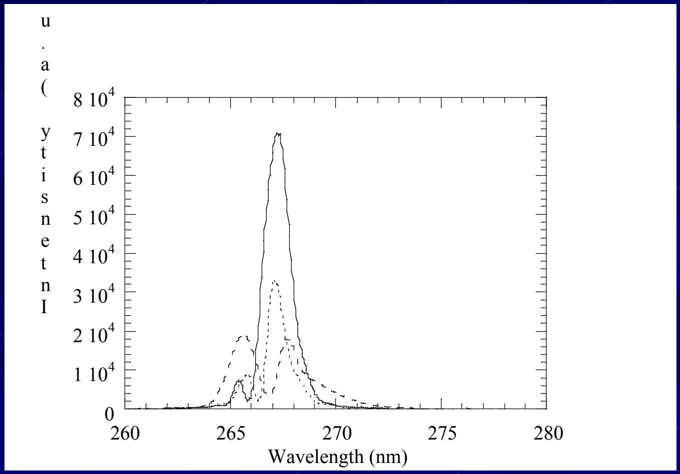
$$K_h = K(-1)^{(h-2)/2} J'_{h/2}(h\xi)$$

for h = 2, 4, …, where $\xi = K^2/(4+2K^2)$.

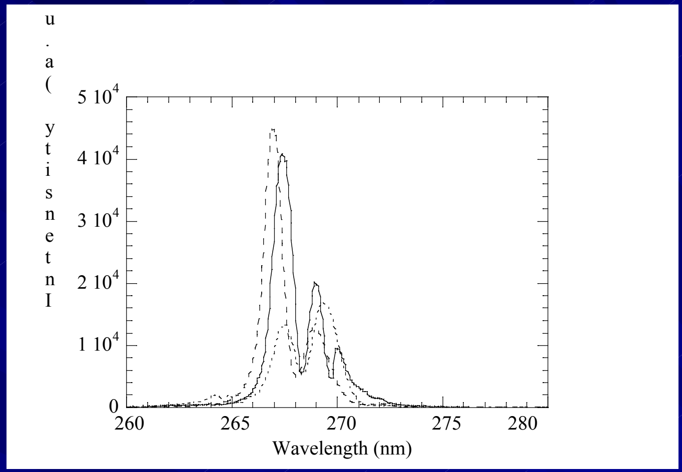
Electron beam measurements taken immediately after the 530-nm and 265-nm UR gain scans on 16 August 2001.

PARAMETER	Value
Beam energy (MeV)	217
Peak current (A)	210
Energy spread (%)	0.1-0.2
Bunch length (fs rms)	340
Charge (pC)	176
Emittance x (μm)	5.9
Emittance y (μm)	6.4

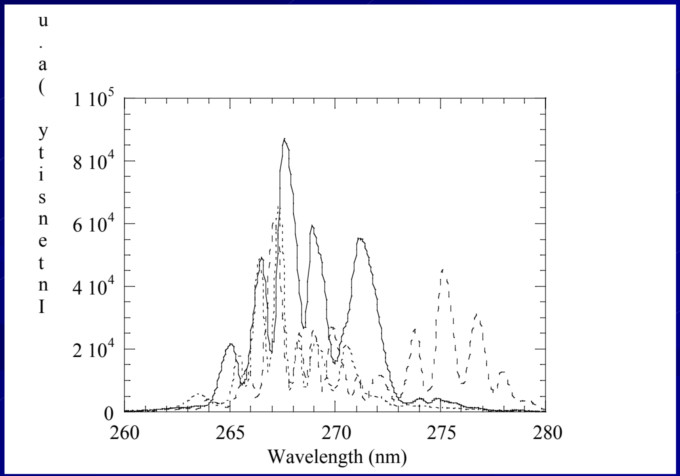
Three measured second harmonic, single-shot spectra using the end-station spectrometer for each undulator/station.

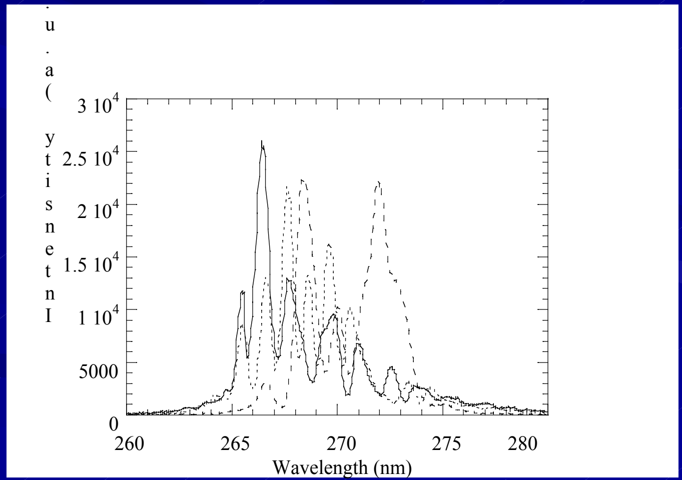


(a) Station 5 (12 m)

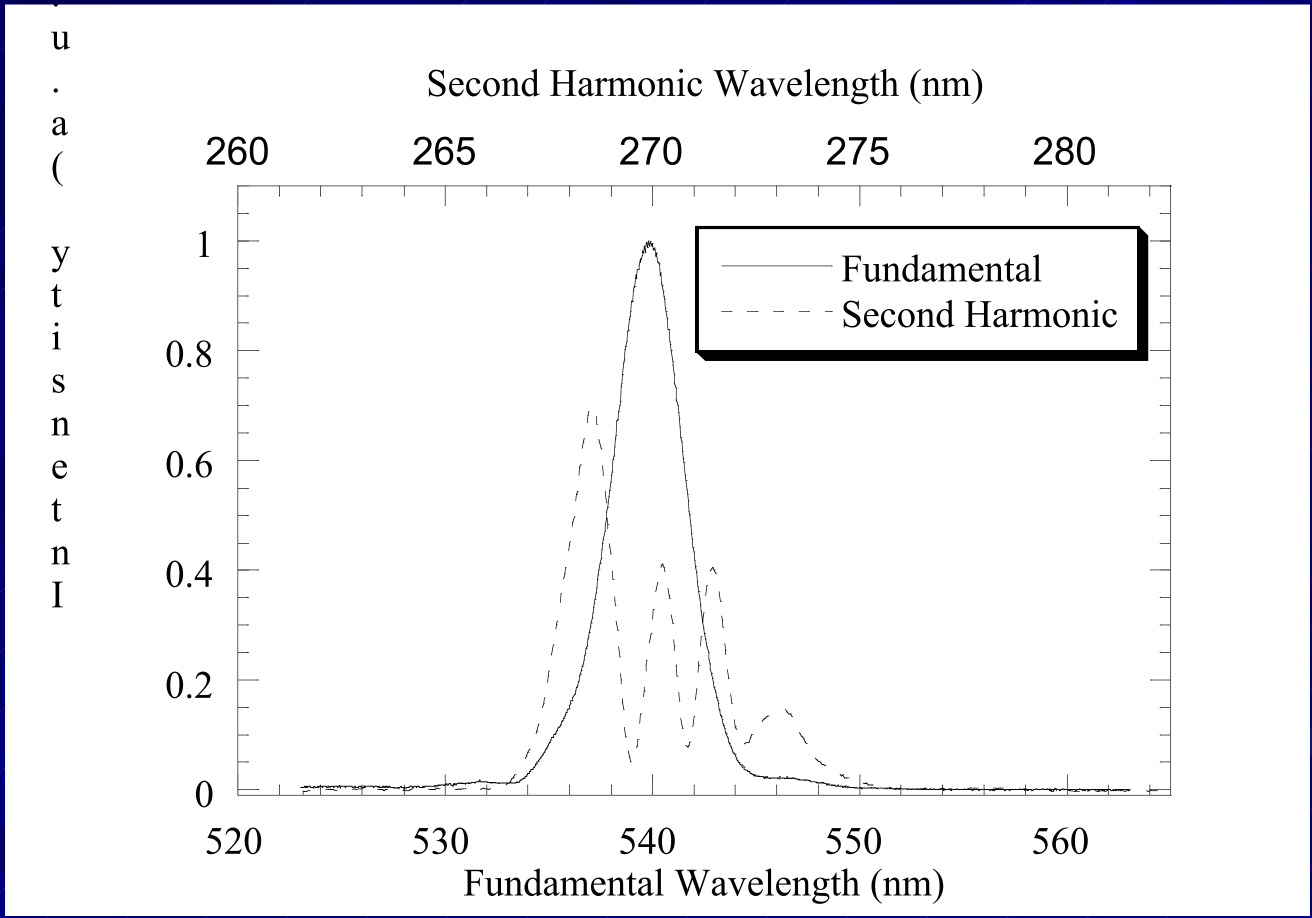


(b) Station 6 (14.4 m)





Simultaneous fundamental and second harmonic spectra after undulator 7 (z = 16.8 m) as measured by the end-station spectrometer.



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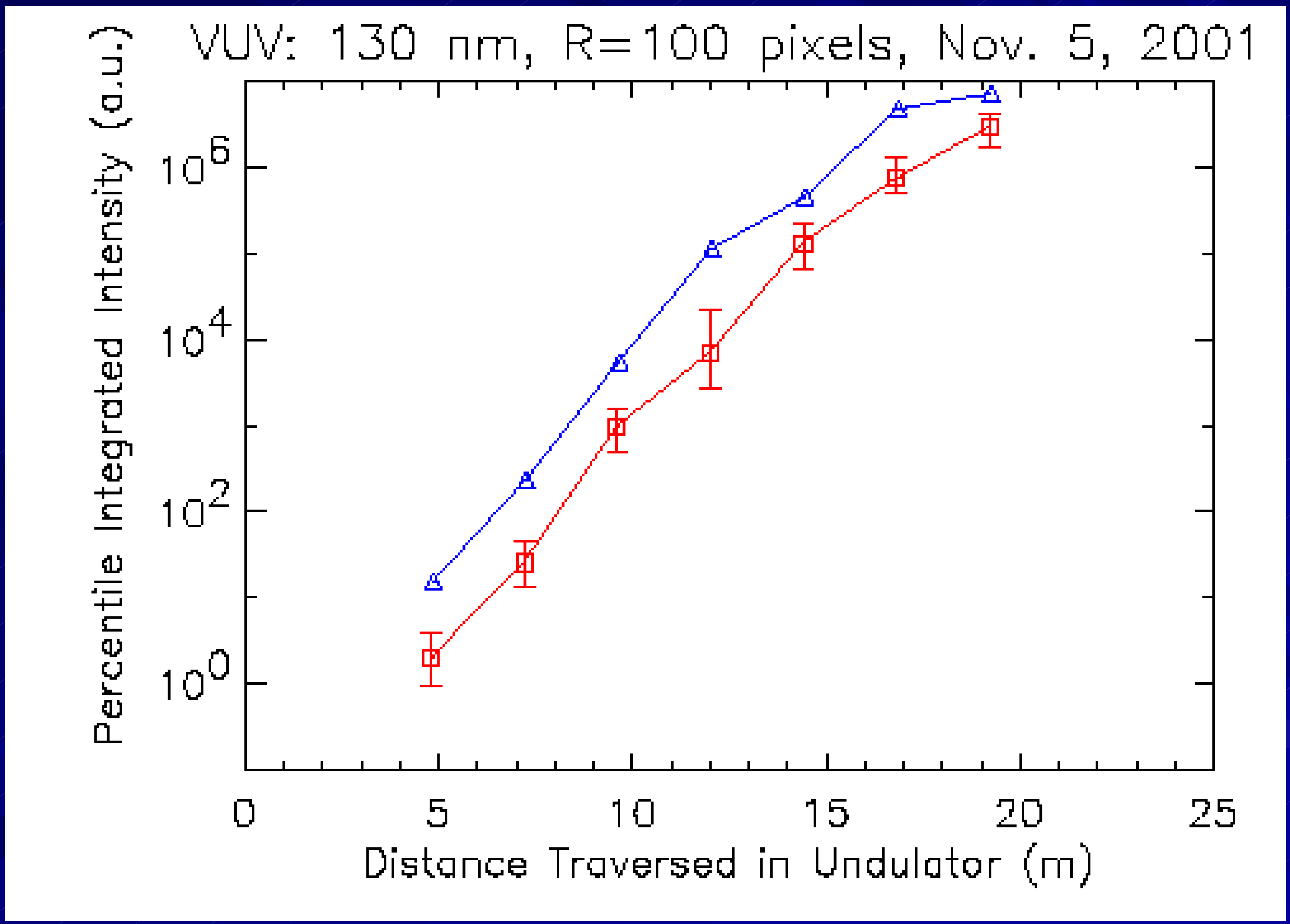
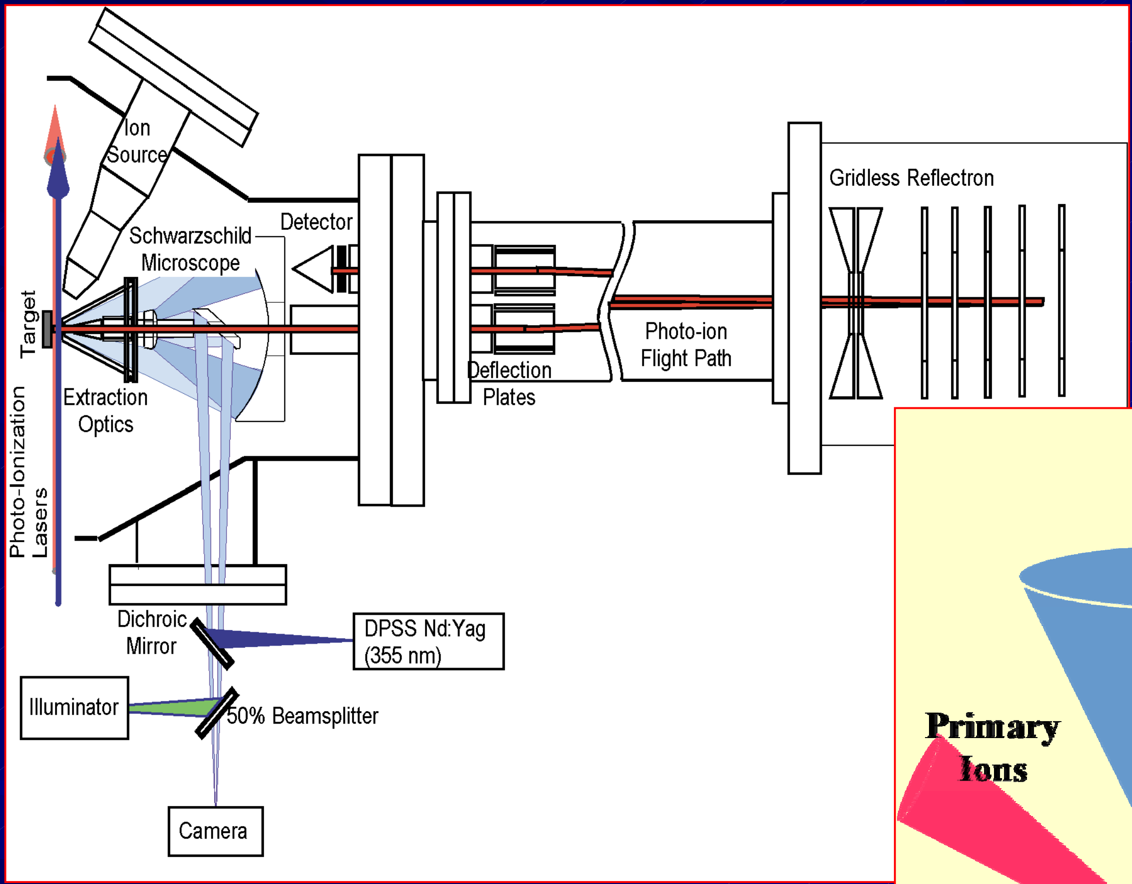
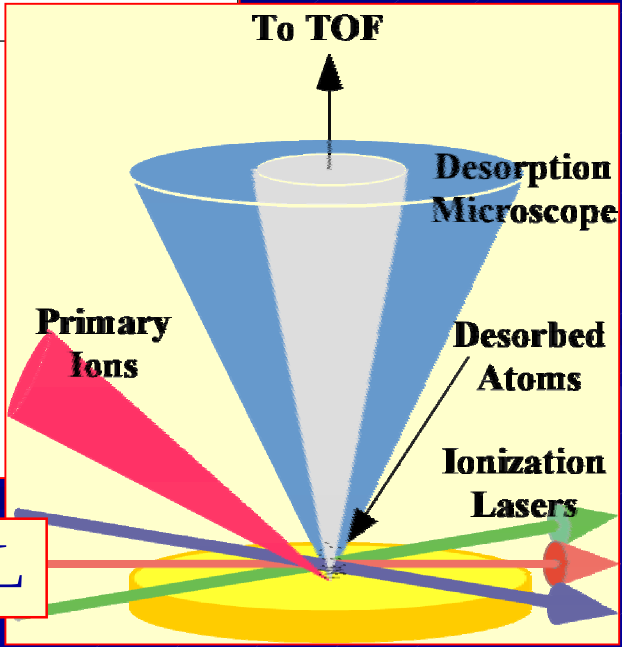
Recent Results at 130 nm



The First APS FEL Experiment

M. Pellin
MSD/ANL





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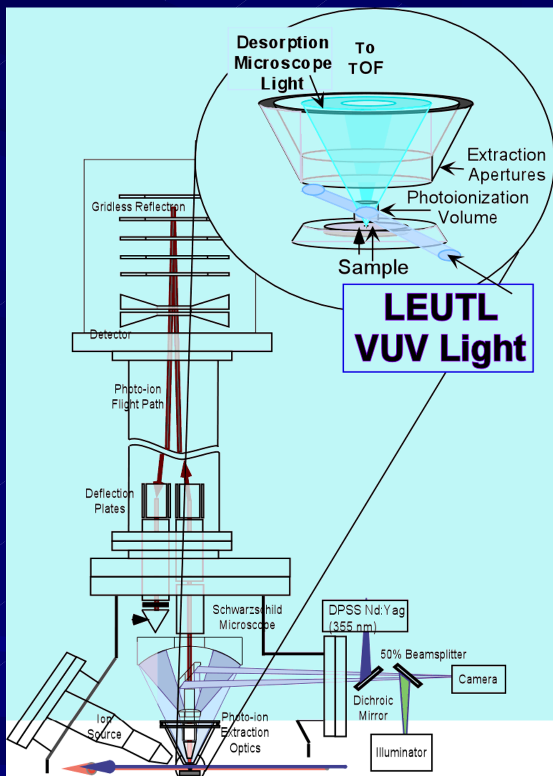
The First APS FEL Experiment

Single Photon Ionization / Resonant Ionization to Threshold (SPIRIT)



M. Pellin MSD/ANL

SPIRIT will use the high VUV pulse energy from LEUTL to uniquely study –

- **Trace quantities of light elements**:
  H, C, N, O in semiconductors with
  100 times lower detection limit
- **Organic molecules <u>with minimal fragmentation</u>**
  cell mapping by mass becomes feasible
  polymer surfaces
  modified (carcinogenic) DNA
  photoionization thresholds
- **Excited states of molecules**
  cold wall desorption in accelerators
  sputtering of clusters

Coming 2002

SASE FELs Planned or Under Study

• LCLS-SLAC	0.15 nm
CDR in preparation.	
• TESLA/FEL DESY	0.1 nm
TDR complete.	
• SCSS-SPring8	> 2 nm
Approved and Funded.	
• SDL-BNL	> 100 nm
Electron beam testing underway.	
• SPARX-Italy	> 1 nm
Funded. In planning.	

Summary

- SASE to saturation has been achieved regularly down to 98 nm at DESY and 130 nm at ANL both at power level and brightness far greater than any other source at these wavelengths. Both are fully tunable over a broad range of wavelengths.
- Initial experiments using this light source have now been done with additional experiments eminent.
- The first experiments are already showing new and unexpected (exciting) results.
- With today's technology we may be able to build a tunable laser using the SASE process down to 1 nm (Note: 2 nm - 4 nm is the "water window")
- Research grade X-ray lasers are on the horizon and I expect to see one functioning (LCLS) within 6 years.